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NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
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SUMMARY PAGE

THE PROBLEM

The dosimetry of microwave and radio-frequency (RF) radiation requires techniques that can evaluate complex patterns of internal energy deposition across a wide range of frequencies. These techniques must also be able to make dosimetric determinations for a variety of laboratory animals as well as man. Microwave and RF dosimetric measurements typically use invasive methods such as implanted temperature probes or electric field probes. Invasive techniques are much more easily utilized in models rather than in live animals. Obviously, realistically shaped models produce more valid dosimetry results as compared to results based on simple spheroidal shapes. Models of primates previously used in this laboratory were contained in bulky low-density foam molds. Those early models could not be positioned in the same fixtures used by live animals during irradiation experiments, and the insertion of temperature probes and field probes was always hampered to some extent by the presence of the large mold. In addition, production of the molds was costly which fact made it difficult to experiment with many sizes of animals. To overcome these drawbacks, realistic models of rhesus (Macaca mulatta) and squirrel (Saimiri sciureus) monkeys were developed using common surgical gloves, gelatinous muscle-equivalent material, and simple fabrication procedures.

FINDINGS

The so-called rubber-glove monkey models have been successfully used for more than three years at this laboratory. Dosimetric analyses using these models have produced results that compare reasonably well to data obtained using live animals and to previously published data.

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The animals used in this study were handled in accordance with the Principles of Laboratory Care established in the "Guide for the Care and Use of Laboratory Animals", Institute of Laboratory Resources, National Research Council, DHEW Publ. No. (NIH) 80-23.

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INTRODUCTION

Publication of the Radiofrequency Radiation Dosimetry Handbook, Second Edition, (4) produced a significant forward step in dosimetric state-of-art for nonionizing electromagnetic radiation (NEMR). That handbook utilized prolate spheroidal computer models to predict specific absorption rate (SAR) in a wide range of animal subjects from insects to man for frequencies from 10 MHz to 10,000 MHz with E-, H- and K-polarization. At first analysis, the handbook appeared to be the long-awaited authoritative panacea of microwave dosimetry, for the experimental results of Gandhi using rats (5) and the theoretical predictions of Chen and Guru (2) seemed to corroborate much of the handbook data. Preliminary results from our laboratory using a limited number of point measurements in a full-size man model at 1.29 GHz also appeared to verify the predictions of the handbook (12).

It must be noted, however, that the authors of the dosimetry handbook clearly stated that their results represented only approximations because the spheroidal models were severely lacking in terms of animal structures such as arms and legs (4). The need for using realistic models was seen in the dosimetric results of Olsen and coworkers (15) in which a 10-kg sitting rhesus monkey model enclosed in a polyurethane mold and irradiated at 1.29 GHz, exhibited a resonant-type microwave absorption in the lower legs of the model causing the overall average SAR to be much higher than theoretically predicted.

Since that time, Lotz (11) has presented experimental evidence to indicate that irradiation near the resonant absorption frequency of rhesus monkeys (Macaca mulatta) produced bioeffects that could not be explained on the basis of theoretically derived SAR.

The original sitting rhesus model developed by Olsen (12) had several drawbacks. First, it represented a larger (approximately 10 kg) animal than was being used in bioeffects experiments by other investigators at the same laboratory (approximately 3-6 kg). Second, the sitting rhesus model was supported by a bulky foamed urethane mold that was required to be in place during experiments. The mold thermally insulated the model, but at the same time it prevented the model from being placed in the same irradiation fixtures as the actual animals. Additionally, the posture of the rhesus model was fixed and could not be used as an independent variable in dosimetric experiments.

To overcome these and other drawbacks, we have developed rhesus and squirrel monkey (Saimiri sciureus) models composed of muscle-equivalent material contained inside specially formed rubber surgical gloves. These "rubber glove models", as they are now identified, have been used for over three years at this laboratory (3, 9) and have proved to be a worthwhile research tool. In the present report, we give the construction details for these models and show dosimetric results obtained with them at 225 MHz, 275 MHz, 1.29 GHz, and 5.6-5.8 GHz.

MATERIALS AND METHODS

Preparation of two surgical gloves is the first step in the construction of the monkey models. We have used size 8 1/2 almost exclusively (see Figure 1A). The index finger and ring finger of each glove are tied off close to the palm and are inverted into the glove as shown in Figure 1B. The middle fingers of the pair of gloves become the head and tail of the monkey while the outside fingers become the arms and legs. Typically, muscle-equivalent material (6) is then stuffed into the gloves until the desired mass is obtained. Approximately 5 kg of material is the maximum quantity for currently available surgical gloves (size 8 1/2) because considerable stretching of the rubber usually occurs during this process (Figure 1C).

A nearly spherical head can be formed by forcing material into the tip of the appropriate finger and then making a constriction just below the head with masking tape to preserve its shape. Similar partial constrictions are used at the proximal end of each limb to prevent material from being pushed back into the torso. Care is taken however, not to produce an electrical discontinuity at these locations. The two gloves are then joined at the palms as sequentially shown in Figure 1D such that a torso of the desired diameter and length results. Masking tape can be used to fasten the filled and formed gloves to each other and to provide extra strength and dimensional stability. Tape is also used to hold the model in the proper position in the foamed polystyrene irradiation restraint chairs that are normally occupied by a monkey during experiments. This is shown in Figure 2.

A B C D

Figure 1

Various stages in the assembly process of a rubber glove primate model.

Figure 2

A muscle-equivalent squirrel monkey model weighing 0.75 kg is shown seated in a foamed polystyrene restraint chair inside an anechoic irradiation chamber. The Vitek temperature probe is shown exiting the head from the rear.

Use of these models in dosimetric experiments usually involves non-perturbing temperature probes or calorimeters. A microwave-transparent temperature probe in muscle-equivalent models provides localized temperature-rise information that is used to calculate SAR for the measured location (8). Calorimeter experiments are used to determine average SAR by obtaining a measure of the total heat deposited in the model by the irradiation. In recent years, twin-well, Dewar-flask, and gradient-layer calorimeters have been used in this application (1, 14, 17). In certain irradiation systems such as waveguides, dosimetric information can be determined directly from RF power measurements using directional couplers and power meters (7, 10).

RESULTS

SAR data presented in this section were obtained with an average of three replications. Standard deviation of the mean SAR was typically 10-15% for all measurements. Since the included SAR data is ancillary to the purposes of this report, specific statistical parameters of each SAR determination have been omitted from the tabular data.

SQUIRREL MONKEY MODELS

Dosimetry at 5.62 GHz was conducted using the 0.75 kg squirrel monkey model shown in Figure 2. This experiment was conducted inside a microwave-anechoic chamber. A Vitek model 101 Electrothermia Monitor (Vitek Inc, Boulder, CO), a microwave-compatible temperature probe, was used to obtain SAR at many locations in the tissue-equivalent model. A saline-filled balloon model was also used to determine whole-body average SAR under identical conditions. Table 1 gives a summary of the dosimetric results.

RHESUS MODELS

Anechoic Chamber Experiments. Dosimetry at three irradiation frequencies was conducted using rhesus monkey models ranging in size from 4.0 to 4.8 kg. Figure 3 is a photograph of a 4 kg model positioned in a microwave-compatible, low-density restraint chair developed in this laboratory especially for rhesus monkey irradiation experiments (18). In addition to temperature probe measurements in the head at 5.8 GHz, average SAR was measured with gradient-layer calorimeters (Thermonetics Inc., San Diego, CA) at 225 MHz and 1.29 GHz. Table 2 gives a summary of rhesus glove-model dosimetric results obtained in microwave-anechoic irradiation chambers.

Circular Waveguide Experiments. A circular waveguide irradiation system for rhesus subjects was recently produced in our laboratory, and a rubber-glove model was used along with live monkeys to dosimetrically analyze the system at 275 MHz (13). The central section of the circular waveguide was made of stainless steel mesh; Figure 4 shows the glove-model rhesus inside the irradiation system, supported by a small foamed polystyrene stand. Gradient-layer calorimeter experiments were used as well as incident, reflected, and transmitted power measurements to obtain dosimetric information. Power measurements were also made when six live rhesus subjects, 3.0-7.2 kg, were individually placed inside the waveguide and irradiated at low power (15 mW) for short periods of time. Table 3 shows comparisons of SAR between the various methods and subjects used in the circular waveguide irradiation system.

Table 1. Dosimetric Results at 5.62 GHz Using a 0.75-kg Rubber-Glove Squirrel Monkey Model Inside a Microwave-Anechoic Irradiation Chamber

MODEL	LOCATION	MEAN SAR[1] $(W/kg)/(mW/cm^2)$	LOCATION	MEAN SAR[1]
Tissue-Equivalent Model	Head, front	0.44	Rt. Calf, center	0.31
	Head, center	0.12	Rt. Foot, center	0.22
	Head, rear	0.02	Left Calf, center	0.47
	Neck, center	0.16	Left Foot, center	0.35
	Chest, center	0.05	Rt. Elbow, center	0.73
			Left Elbow, center	0.11
Saline-Filled Balloon Model	Whole-body	0.18		

[1]SAR results were based on Vitek temperature probe measurements.

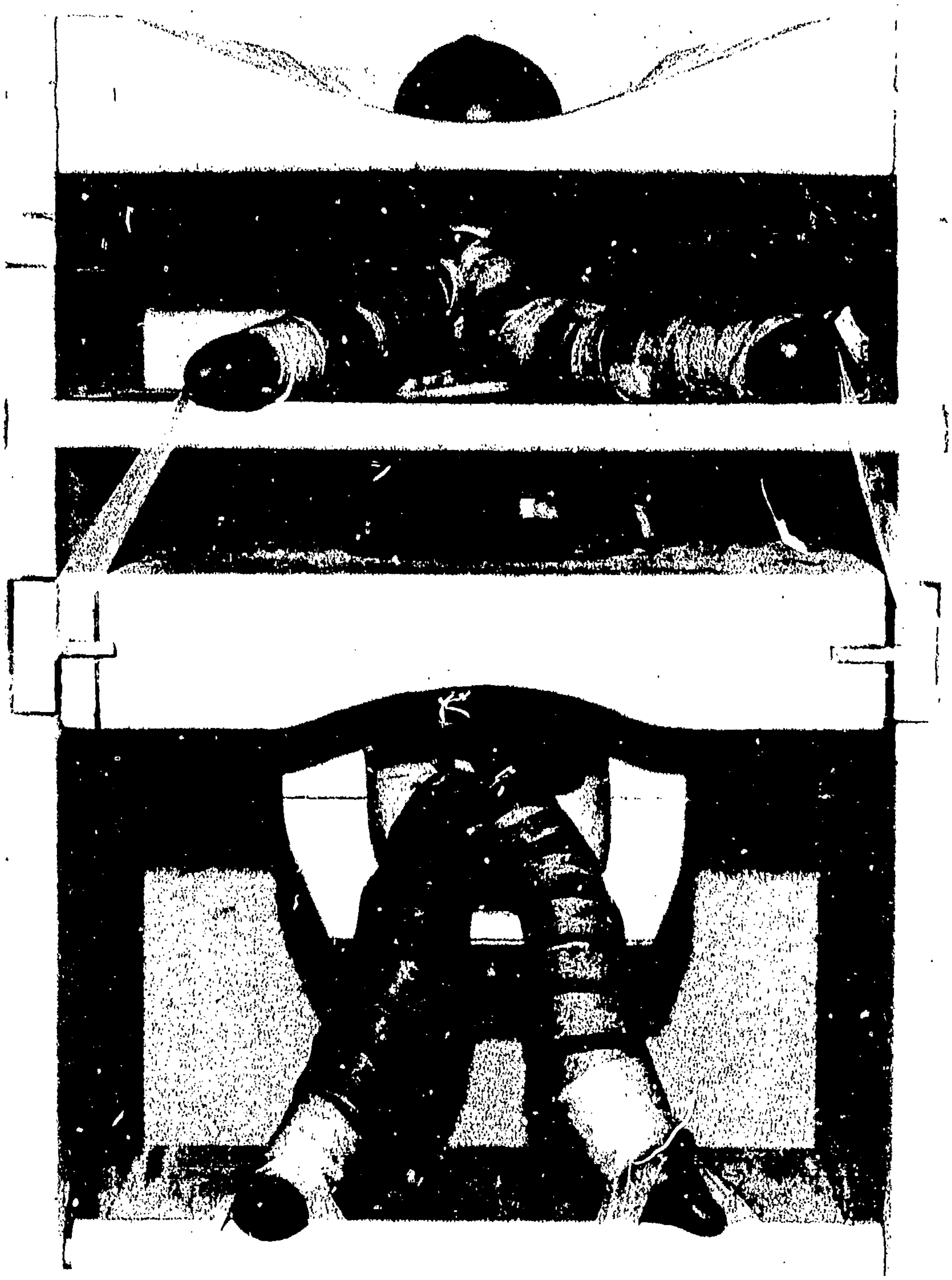

Figure 3

A 4-kg rhesus model is shown in a restraint chair used during irradiation experiments.

Table 2. Dosimetric Results Using Muscle-equivalent Rubber-glove Rhesus Monkey Models Inside Microwave-anechoic Irradiation Chambers

Model	Frequency	SAR Measurement Method	Location of Measurement	Mean SAR (W/kg)/(mW/cm^2)
4.0 kg	225 MHz	Gradient-layer Calorimetry	Whole-body	0.45
4.0 kg	1.29 GHz	Gradient-layer Calorimetry	Whole-body	0.14
4.8 kg	5.80 GHz	Temperature Probe Thermometry	Head, front	0.29
			Head, center	0.029

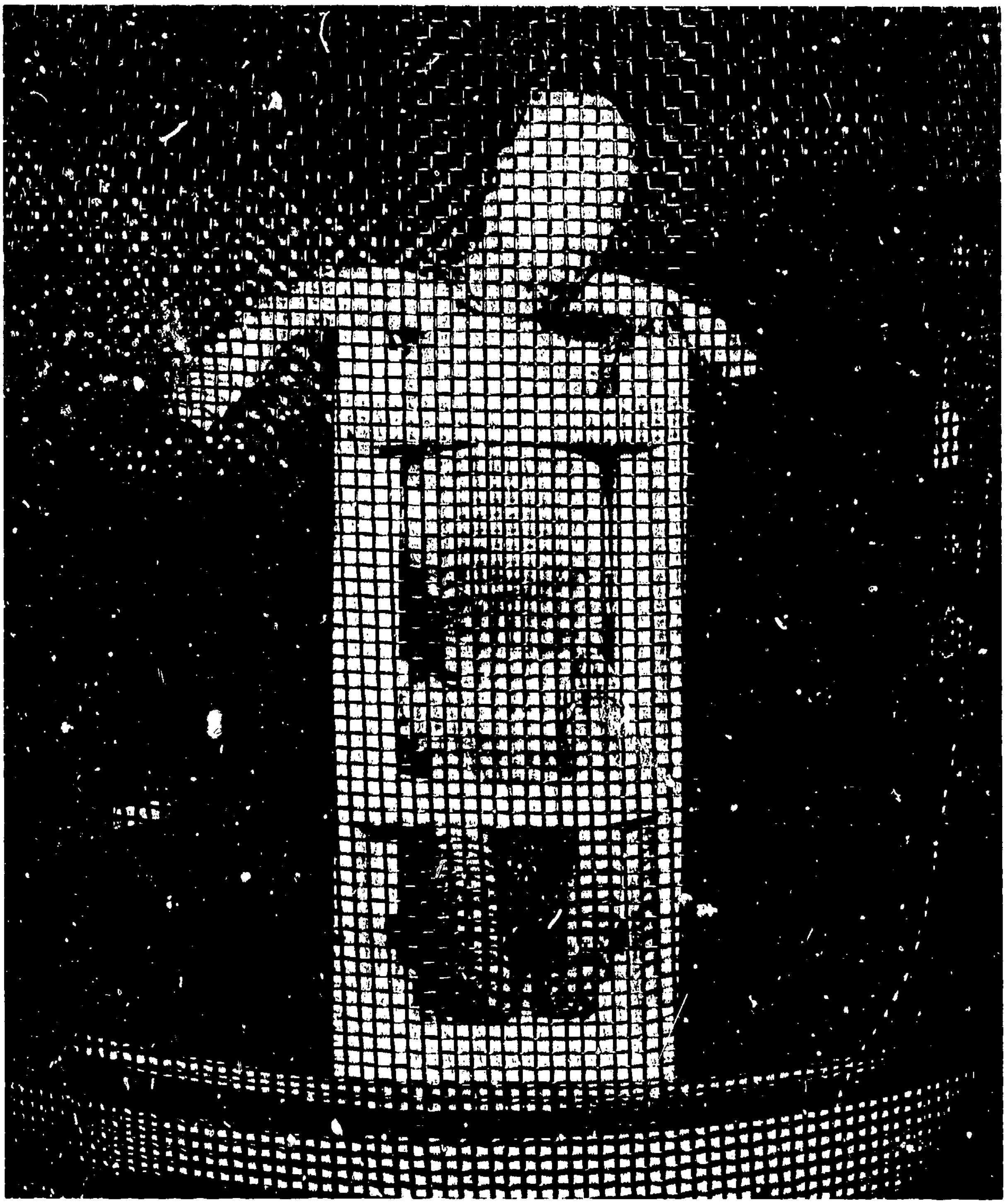

Figure 4

A 4-kg rhesus model is shown inside a 275 MHz circular waveguide irradiation system that was designed specifically for chronic irradiation experiments with rhesus monkeys.

Table 3. Comparison of Dosimetric Results between a 4-kg Muscle-equivalent Rubber-glove Rhesus Monkey Model and Live Rhesus Monkeys Exposed in a 275-MHz Circular Waveguide Irradiation System

Subject	Mean Absorption from Power Meter Measurements*	Mean Absorption from Calorimeter Measurements*	Mean SAR** (W/kg)/(mW/cm^2)
Six Rhesus Monkeys 3.0-7.2 kg	33.6		0.33
4.0 kg Rhesus Monkey Model	30.2	24.3	0.35 (From Power Meter Measurements) 0.28 (From Calorimeter Measurements)

* RF absorption is given as percentage of net input power.

** Average power density was determined by dividing net input power by waveguide cross section, 4560 cm^2.

DISCUSSION

The rubber-glove monkey models for microwave dosimetry have proved to be very useful tools in the bioelectromagnetic research conducted at this laboratory. Although the size of our models was limited to about 5 kg, larger models should be possible if extra-large gloves were used. The fact that the models were not thermally insulated represents a significant limitation in calorimeter experiments. Much care must be used in order to prevent microwave-induced heat from leaving the model before it is secured inside the calorimeter. The magnitude of this problem is seen in the disparity between calorimeter measurements of SAR and that derived from instantaneous power meter measurements using the 275 MHz circular waveguide system (Table 3). Calorimeter measurements averaged 20% lower than the instantaneous value of SAR based on incident, reflected, and transmitted power. The explanation for this disparity is that much heat was lost from the model during and immediately after the irradiation period. The heat loss during irradiation was minimized by keeping the average temperature rise in the model to less than 1 °C in order to avoid large thermal gradients that promote heat transfer by convection and conduction. The post-irradiation heat loss could not, however, be minimized because of the time required to open the waveguide by hoisting the heavy upper tuning section out of the way. Typically, several minutes had elapsed before the model was sealed inside the calorimeter, and it is suspected that the major fraction of heat loss occurred during that period. In a typical anechoic chamber experiment, the model can be removed from the chamber and placed in the calorimeter in a matter of seconds rather than minutes. Post-irradiation heat loss is, therefore, greatly reduced.

Comparison of the data in Tables 1-3 to previously published information shows varying degrees of agreement. The 10-kg sitting rhesus model first used by Olsen and coworkers (15) exhibited a mean SAR of 0.155 $(W/kg)/(mW/cm^2)$ at 1.29 GHz, a value close to the glove-model result given in Table 2 for a comparable configuration. Agreement was not as good at 225 MHz where the sitting rhesus exhibited a mean SAR of 0.285 $(W/kg)/(mW/cm^2)$ (16) as compared to 0.45 $(W/kg)/(mW/cm^2)$ for the rubber glove model. The second edition dosimetry handbook (4) typically predicts SARs much lower than those observed with both squirrel monkey and rhesus monkey rubber glove models. A principal reason for these differences is illustrated in the SAR data of the limbs of the squirrel monkey model in Table 1. These SAR values are the highest of any in the entire model; therefore, it is reasonable to expect that a theoretical model that ignores the limbs would predict a relatively low average SAR.

In conclusion, useful tools for RF and microwave dosimetry have been developed in the form of easily constructed, tissue-equivalent primate models. The models are made from materials commonly found in laboratories that study microwave bioeffects, and no specialized apparatus is required in the fabrication process. Repeated use can be made of the models without significant dehydration or other changes in physical properties, and even though they are not thermally insulated, calorimetric dosimetry methods can be successfully applied as long as due consideration is given to important thermodynamic details.

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Common surgical gloves and a water-based, muscle-equivalent material were used to produce realistic models of rhesus (*Macaca mulatta*) and squirrel (*Saimiri sciureus*) monkeys for use in microwave and radio-frequency (RF) dosimetry. These models represent an improvement over previously used primate models that were typically encased in bulky foamed plastic molds. The so-called rubber-glove monkey models did not require a mold for support, and therefore the models could be placed in the same restraint devices as

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used by live animals during various microwave and RF irradiation experiments. The rubber-glove models, moreover, provide the facility of easily changing the relative positions of the limbs, in contrast to the fixed posture of foam-encased primate models. Dosimetric results were obtained in a variety of configurations using the rubber-glove model. Specific absorption rate (SAR) is given for the plane-wave irradiation of the rubber-glove models at 225 MHz, 1.29 GHz, and 5.6-5.8 GHz. Additional SAR data is given for a rhesus monkey model inside a 275-MHz circular waveguide irradiation system.